Analytical Formulation for Strength Prediction of orthogonal loaded, cold bonded Insert Load Introductions in Sandwich Elements

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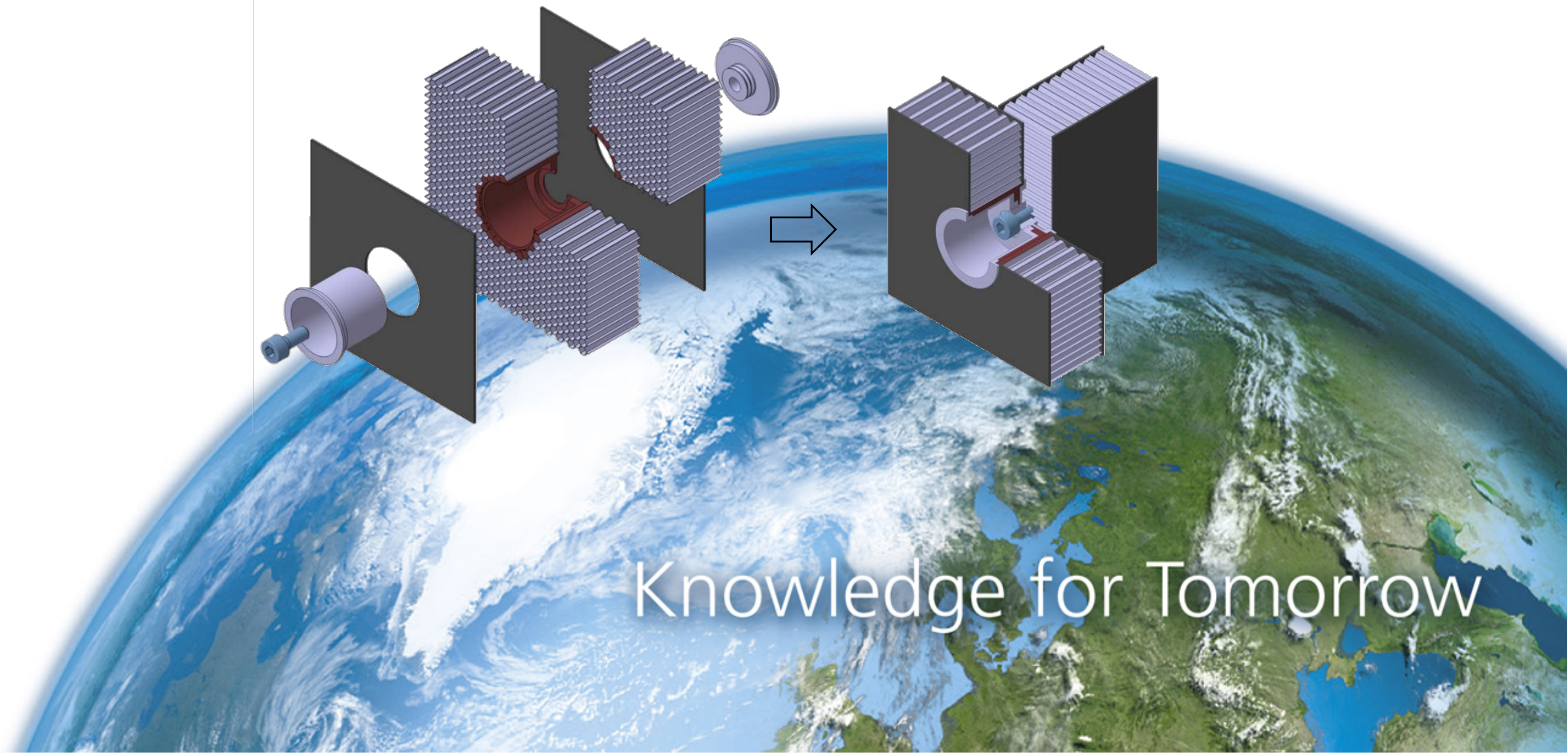

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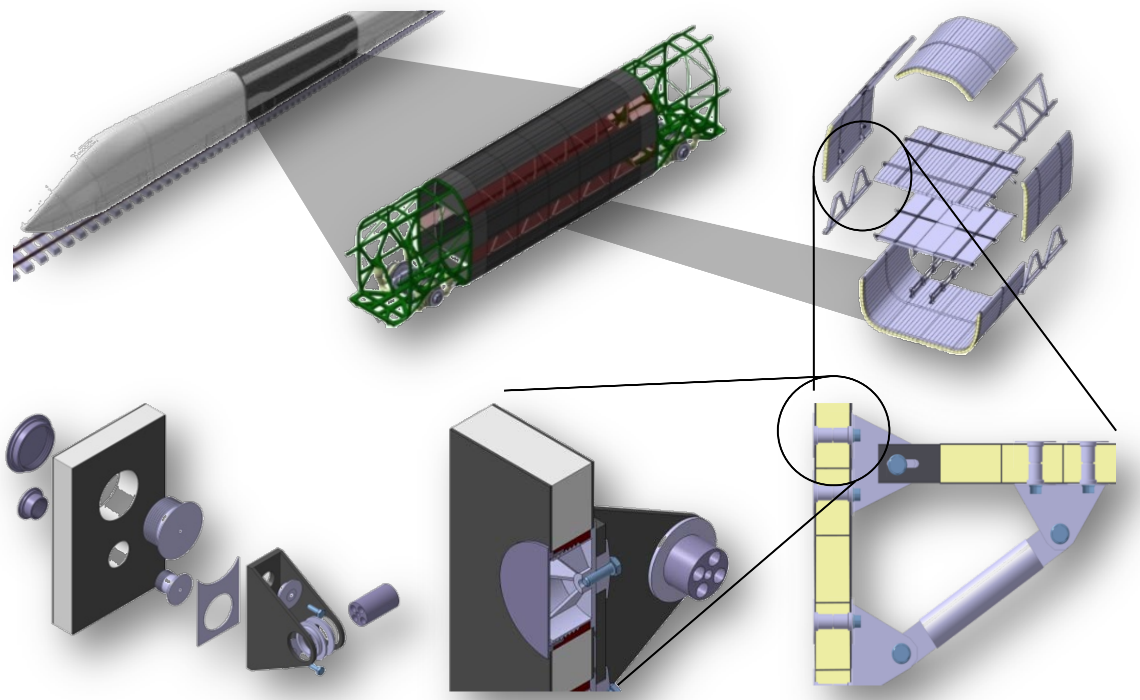
1. Motivation:
Applications of Insert Load Introductions in Sandwich Structures

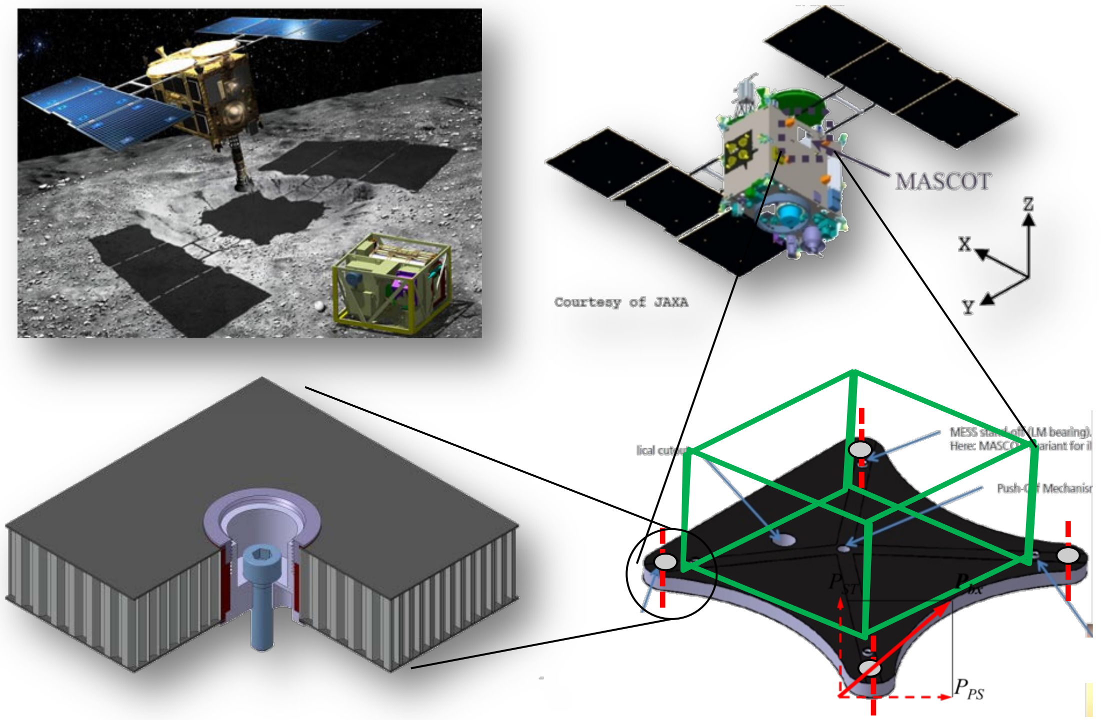
Example 1, ground transport: DLR NGT passenger train concept



Structural, **heavy load connections** with insert elements with the possibility for disassembly, (**60 connections**, ∅ = **46 – 176mm**) [1].

Railway vehicles: **10€ - 60€/kg** [2]

Example 2, aerospace: MASCOT 2 lander, AIM mission



Sometimes numerous detachable connections in e. g. communication satellites; "**up to 25.000 inserts** in a satellite structure" [3].

Aerospace: **10.000$ - 50.000$/kg** [4-6]

→ **Simple sizing method for a minimization of the mass of numerous insert load introductions exposed to different local conditions.**

[1] Wolff, Johannes und Skibbe, Jan. 2016. 2016-06-23_NGT_III_MS16201603_Optimierung_Verbindungselemente_abgeschlossen_v0-21_JWo_JSk.docx. v0-22 [Hrsg.] DLR Deutsches Zentrum für Luft- und Raumfahrt. [Bericht]. Braunschweig, Germany : s.n., 23. 06 2016. Projekt NGT III (Next Generation Train III).
[2] . Nickel, F. Fischer, M. Friedrich, C. Hühne, H. Köke, J. König, G. Kopp und J. Wolff, Projektstudie: Einsatz von CFK-Leichtbau-Faserverbund-Technologien im Schienenfahrzeugbau, DLR, Hrsg., Braunschweig: Meinders & Elstermann, 2016.
[3] RUAG Schweiz AG . Automating inserts for sandwich panels. Vol. 9 [Hrsg.] RUAG Schweiz AG RUAG Space. *Composites World.* [Article]. s.l., Germany : Gardner Business Media, 09 2015. Bd. 1, S. 12.
[4] Kim, Byoung Jung und Lee, Dai Gil. Development of a satellite structure with the sandwich T-joint. [Hrsg.] Korea Advanced Institute of Science and Technology Department of Mechanical Engineering. *Composite Structures 92.* s.l., South Korea : Elsevier Ltd, 2009. Bd. 92. Paper.
[5] Brosius, Dale. Outer space: The "final frontier" is exciting again! [Hrsg.] Knoxville USA Institute for Advanced Composites Manufacturing Innovation IACMI. *Composites World.* [Article]. Knoxville, USA : s.n., 09 2015. Bd. Vol. 9, 1, S. 6.
[6] Kim, Byoung Jung und Lee, Dai Gil. Characteristics of joining inserts for composite sandwich panels. [Hrsg.] Korea Advanced Institute of Science and Technology Department of Mechanical Engineering. *Composite Structures.* s.l., South Korea : Elsevier Science Ltd. , 2008. Bd. 86, S. 55–60.

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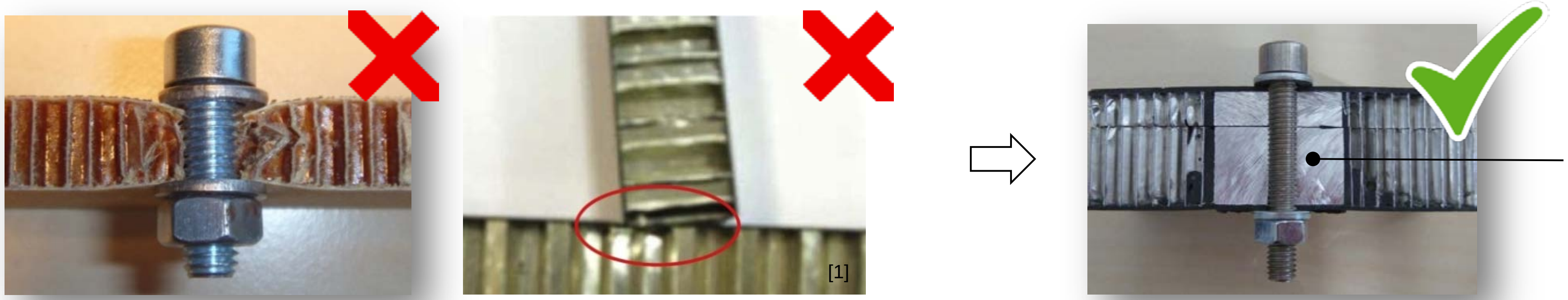
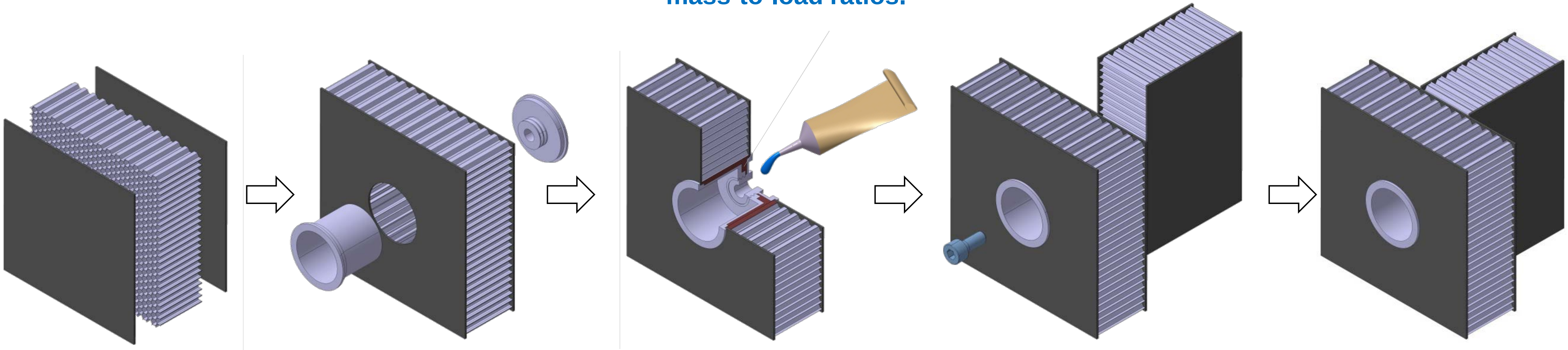
2. Problem task: Demand of Insert sizing Approach

Why insert elements in sandwich structures?



Local core support element (“insert”) to resist the screw clamping force and to offer a smooth transition of structural loads into the adjacent sandwich structure.

→For detachable load introductions in sandwich elements, only connections with core support elements („inserts“) offer sufficient mass-to-load ratios.

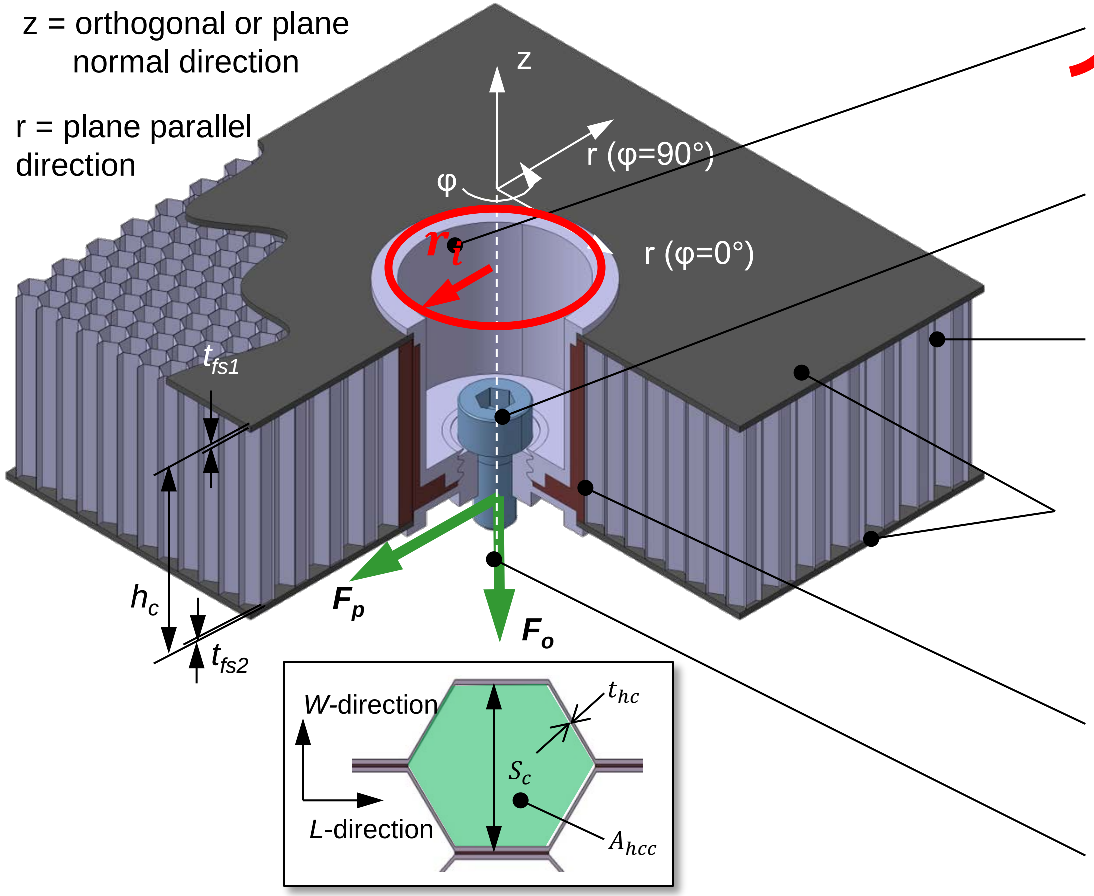


→Focussed: Cold-bonded, through-the-thickness insert elements with core connection via potting compound.

[1] Kim, Byoung Jung und Lee, Dai Gil. Development of a satellite structure with the sandwich T-joint. [Hrsg.] Korea Advanced Institute of Science and Technology Department of Mechanical Engineering. *Composite Structures 92.* s.l., South Korea : Elsevier Ltd, 2009. Bd. 92. Paper.
[2] VDI-Gesellschaft Entwicklung Konstruktion Vertrieb. VDI 2230 Systematic calculation of high duty bolted joints - Joints with one cylindrical bolt. [Hrsg.] VDI Verein Deutscher Ingenieure. *VDI-Guidelines.* [Giudeline]. Düsseldorf, Germany : Beuth Verlag GmbH, 02 2003. Bd. Part 1, 10.02, S. 1 -172.
[3] **Hexcel Corporation.** HexWeb® CR III product data. [Hrsg.] Hexcel Corporation. [Specification data sheet]. 2015. www.hexcel.com.
[4] **Plascore Incorporated.** PAMG-XR1 5056 Aluminium Honeycomb. v12.14 [Datenblatt]. Zeeland, Michigan, USA : s.n., 2014. www.plascore.com.
[5] **Euro-Composites S. A. .** Mechanical properties of ECA Honeycomb material . [Hrsg.] 2, rue Benedikt Zender (Z.I.), B.P.24, L-6468 Echternach EURO-COMPOSITES® S.A. [data Sheet]. 2010. S. 1. https://www.professionalplastics.com/professionalplastics/NomexHoneycomb-AerospaceQuality.pdf. EC536-1 3e/2010-02-23 Version 1.0.

2. Problem task: Demand of Insert sizing Approach

Specification: Basic Model



Insert element
- Machined aluminium.
- Through-the-thickness (“ttt”).
- Core connected (by potting compound).
- Two-part.

Screw
- Steel, aluminium, titan,…
- Shaft length and screw head as short as possible, sizing of shaft diameter according to VDI 2230 [2].

Honeycomb core
- Aluminium foil
- Foil thicknesses t_{hc}= 0,018 - 0,06mm (0.0007’’- 0.0025’’).
- Cell sizes S_c= 3,2, 4,8, 6,4 and 9,6mm (1/8’’ to 3/8’’).
- Anisotropic properties [3-5].

Symmetric face sheets
- Endless carbon or glass fiber rovings.
- Quasi-isotropic stacking sequence of woven or unidirectional layers.
- Epoxy matrix.
- Face sheet thicknesses t_{fs}= 0,3 - 3mm.

Potting compound

Structural adhesive
- 3M ScotchWeld DP490
- EC-9300 FST B-A.

Critical load proportion

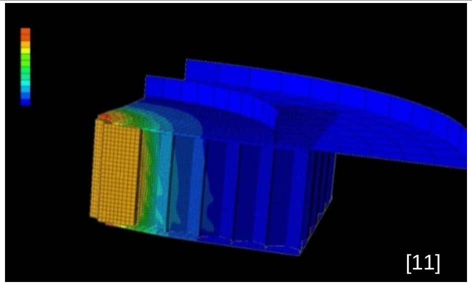
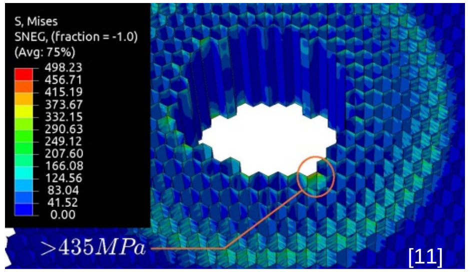
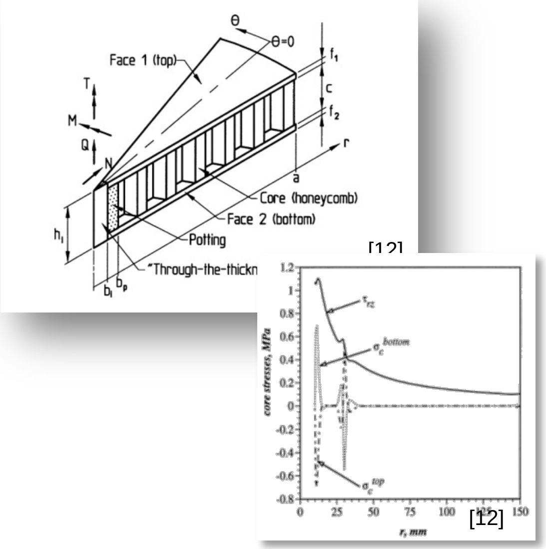
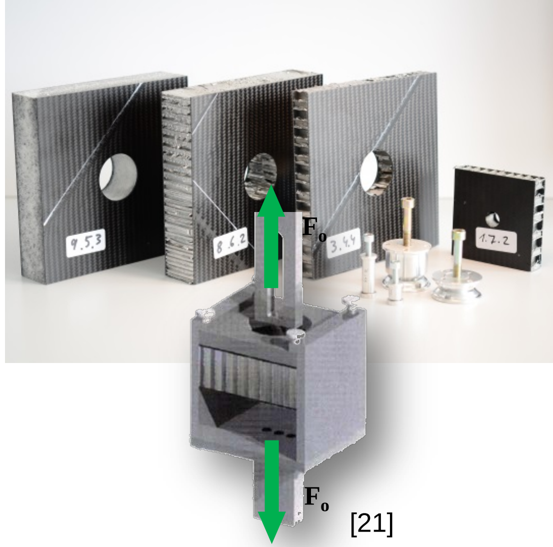
Orthogonal resp. pull-out proportion of structural load F_o.

→ **Screw and the insert element add the highest mass proportions, a minimization of the insert radius most beneficial!**

→ **Objective: Minimization of the insert element radius for a given maximal orthogonal load.**

3. State of the Art

Insert load Introduction Description Methods

	Simulation with FE-model	Higher order sandwich theory	Empirical approaches	"Simple" analytic theory
	High resolution FE-modelling of individual insert load introductions [1-10].	Utilization of higher order sandwich plate theories (HSAPT) on (local) insert load introductions [12-18].	Testing of all necessary, differing insert element - sandwich configurations [19,20].	Sizing approach derived from failure / damage behavior [12-14, 24-2].
	 [11]  [11]	 [12] [12]	 [21]	 $$\tau_{c,rz}(r,z) = \frac{Q_c}{A_c(r)}$$ $$\cdots = \frac{F_{op} \cdot \eta_{ld}}{a_1 \cdot \tau_{c,rz,crit,eff} \cdot (t_{fs1}+h_c) \cdot 2\pi} - S_c \cdot \frac{\cdots^2}{a_1}$$
Pro	Precise results, evaluation of local phenomena is possible.			Simple and fast method on hand calculation level.
Con	Excessive effort for a sizing of numerous inserts exposed to various local conditions.			Less quality of results, not available for the relevant insert type.

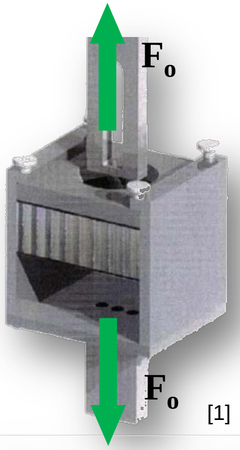
→ All models / theories, except from the simple analytical theory, are too complex for a sizing of numerous insert load introductions!

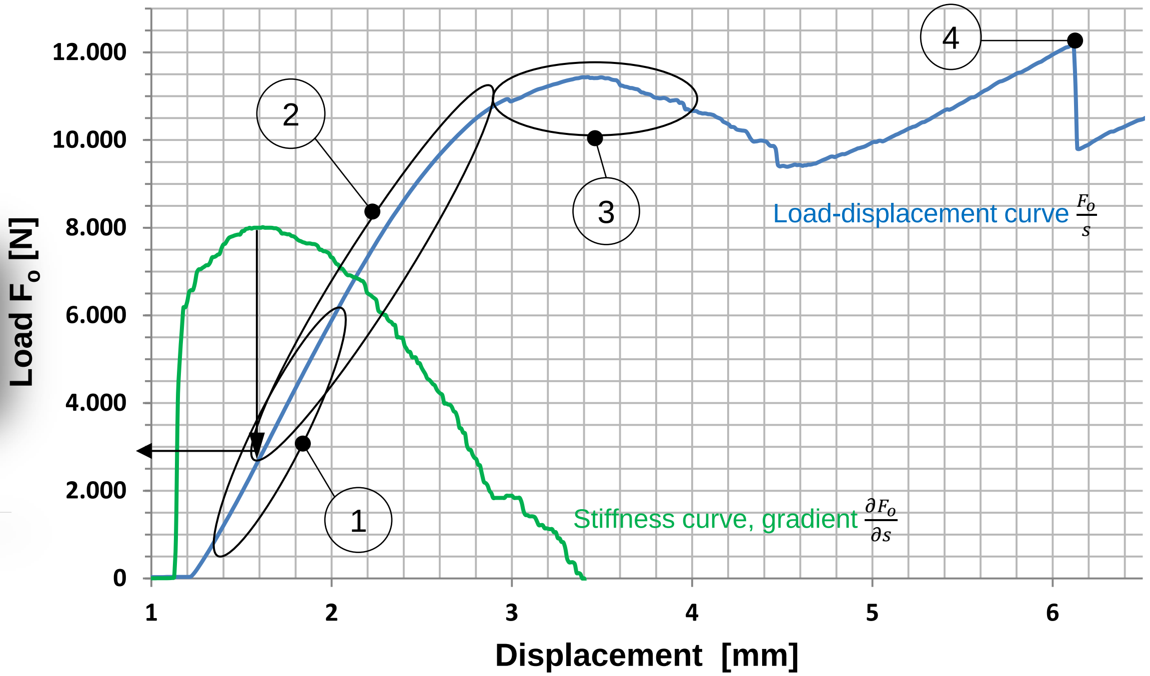
Core shear failure freecut sample

4. Insert sizing Approach

Failure Behavior of ttt-Insert Load Introductions in Honeycomb Sandwich Elements

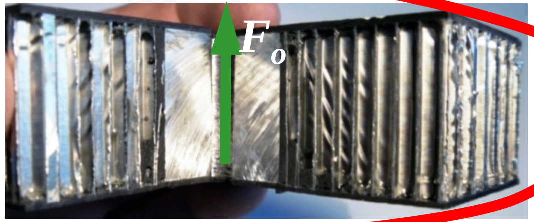
Typical load-deflection curve



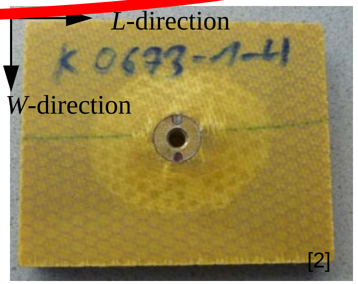


Damage characteristics of ttt-inserts

1. Elastic shear deformation of the core material near to the insert element
2. Irreversible resp. plastic shear deformation of core material.



3. Failure of core-face sheet bonding around the insert element, membrane formation of the face sheet.



4. Disintegration of insert element.

First relevant failure = Plastic core shear damage arround the insert load introduction.

→ Request for the sizing formulation: No plastic core shear failure should occure until the limit load level $F_o = F_{o,ll}$!

[1] Block_J_Carbon_fibre_tube_inserts_(Part_2)_Technical_Note_2_Test_Plan_and_Test_Procedures_ROSETTA_DLR_FA_IB_131-2006-14
[2] Wolff, Johannes , et al., et al. Abschlussbericht zum Teilprojekt des DLR im Verbund, Projekt InGa (Innovative Galley). [Hrsg.] FA-FLB Deutsches Zentrum für Luft- und Raumfahrt Braunschweig. [Report]. Braunschweig, Germany : s.n., 22. 03 2016. S. 192. DLR-IB-FA-BS-2016-102.

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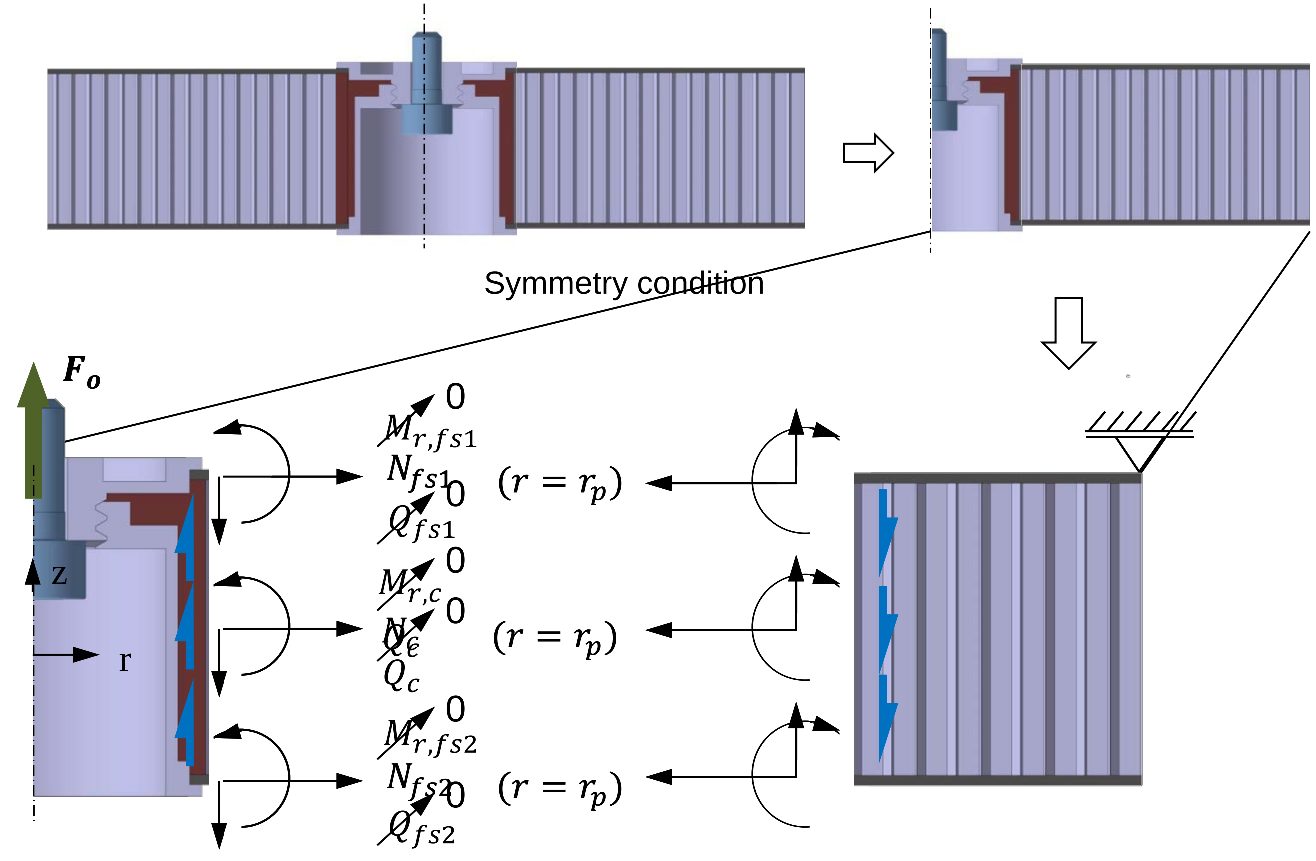
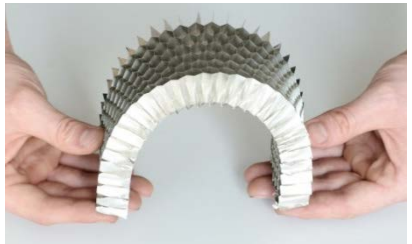
4. Insert sizing Approach

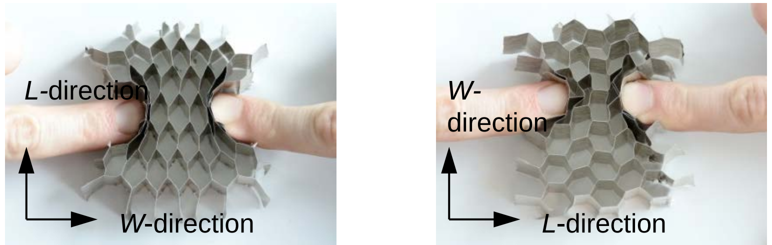
Model Development: Basics, Honeycomb material Behavior



Free cut at junction between potting compound and honeycomb core ($r = r_p(\varphi)$).



Bending resistance of honeycomb core $\downarrow\downarrow \rightarrow M_{r,c} \approx 0$



Compression resistance of honeycomb core in r, φ-plane $\downarrow\downarrow \rightarrow N_c \approx 0$

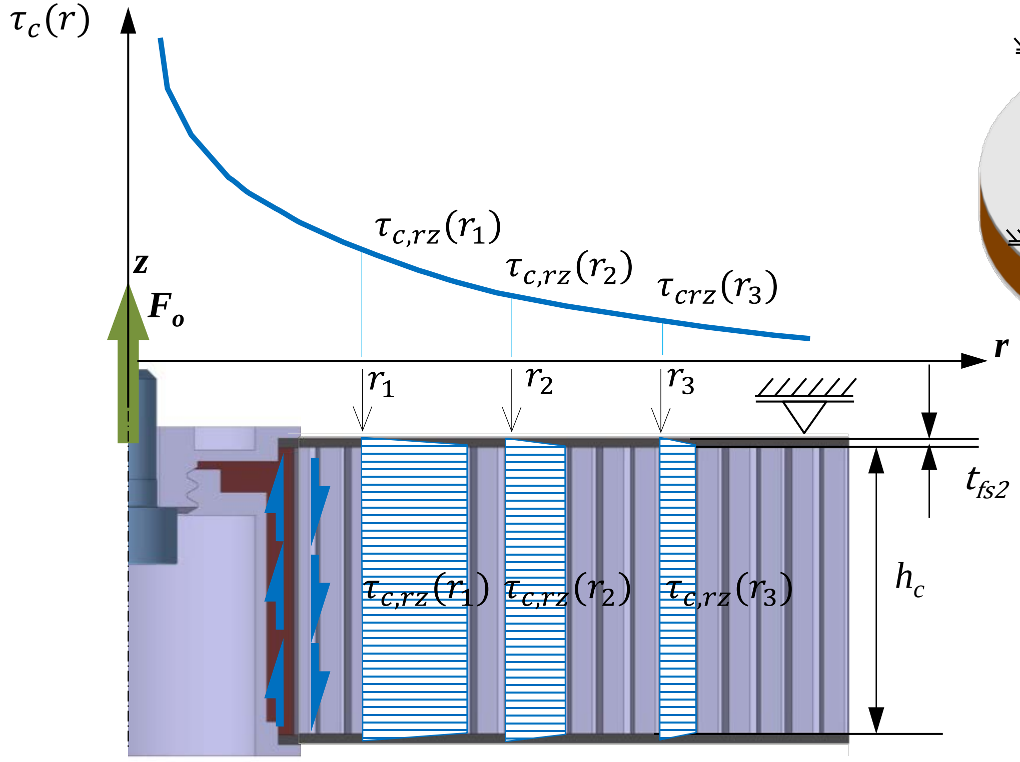
In case of face sheet bending resistance $\downarrow\downarrow \rightarrow Q_{fs} \approx 0,\ M_{r,fs} \downarrow$

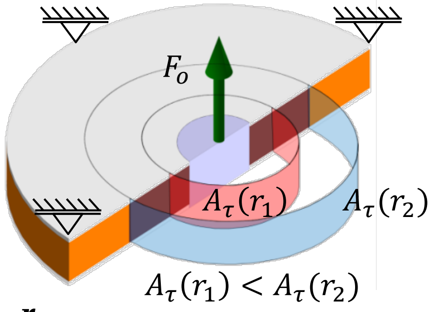
→ For simplicity of the sizing approach, only the equilibrium of forces in the core are considered.

4. Insert sizing Approach

Model Development: Local Core Shear Force, Stress and Area Relation

Relation between core shear force, core shear stress and shear area





Approaching the insert load introduction, the core shear stress increases with $1/r$ due to the decreasing effective shear area $A_\tau(r)$.

Development of sizing formula:

$$\tau = \frac{Q}{A}$$

$$\Downarrow$$

$$\tau_{c,rz}(r,z) = \frac{Q_c}{A_\tau(r)}$$

$$\Downarrow$$

with $A_\tau(r) = 2\pi \cdot r \cdot (t_{fs1} + h_c)$

$$\Downarrow$$

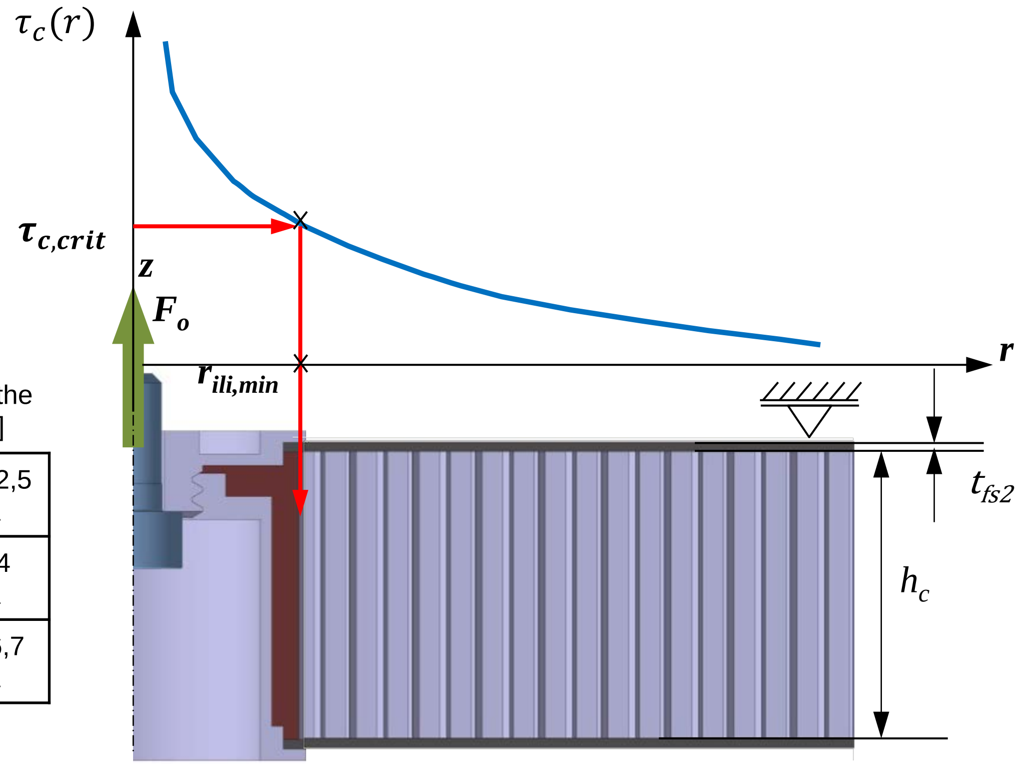
$$\tau_{c,rz}(r) = \frac{Q_c}{2\pi \cdot r \cdot (t_{fs1} + h_c)} \quad [1-4]$$

[1] ECSS European Cooperation for Space Standardization. Space Engineering Insert Design Handbook. [Hrsg.] ESA-ESTEC. Noordwijk : s.n., 2011. Bde. ECSS-E-HB-32-22A.
[2] Bozhevolnaya, Elena, et al., et al. Local effects across core junctions in sandwich panels. [Hrsg.] Aalborg University Institute of Mechanical Engineering. Composites Part B: engineering. Pontoppidanstraede 105, DK-9220 Aalborg East, Denmark : Elsevier Science Ltd., 2003. S. 509-517. doi:10.1016/S1359-8368(03)00043-X.
[3] Heimbs, Sebastian und Pein, Marc. Failure behaviour of honeycomb sandwich corner joints and inserts. EADS Innovation Works. Composite Structures 89 : Elsevier, 2009. S. 575–588, Paper.
[4] Bianchi, G. und Aglietti, G. S. Static performance of hot bonded and cold bonded inserts in honeycomb panels. [Hrsg.] University of Southampton School of Engineering Sciences. Journal of Sandwich Structures and Materials. [Paper]. s.l., UK : Sage publications Ltd., 2010. Bd. 0, S. 1099-6362. DOI: 10.1177/1099636209359840.

4. Insert sizing Approach

Basics: Core shear – pull out force relation: Development of sizing formula

Core shear stress course



Ciritical shear stiffness of the core material $\tau_{c,rz,crit}$ [1]

Foam	0,25 – 2,5 MPa
Honeycomb, Nomex	0,3 - 4 MPa
Honeycomb, Aluminium	0,3 – 6,7 MPa

Development of sizing formula:

$$\tau_{c,rz}(r) = \frac{Q_c}{2\pi \cdot r \cdot (t_{fs} + h_c)}$$

$$\Downarrow$$

$$r = \frac{Q_c}{\tau_{c,rz}(r) \cdot (t_{fs} + h_c) \cdot 2\pi}$$

At the location, where:

$$\tau_{c,rz}(r) = \tau_{c,rz,crit} \rightarrow r = r_{ili,min}$$

r becomes:

$$\boldsymbol{r_{ili,min} = \frac{Q_{z,ll}}{\tau_{c,rz,crit} \cdot (t_{fs} + h_c) \cdot 2\pi}}$$

[1-4]

Approach:

→ The extent of the insert load introduction must reach exactly to $r = r_{ili,min}$, where the local core shear stress $\tau_{c,rz}(r)$ equals the core material shear strength $\tau_{hc,crit}$.

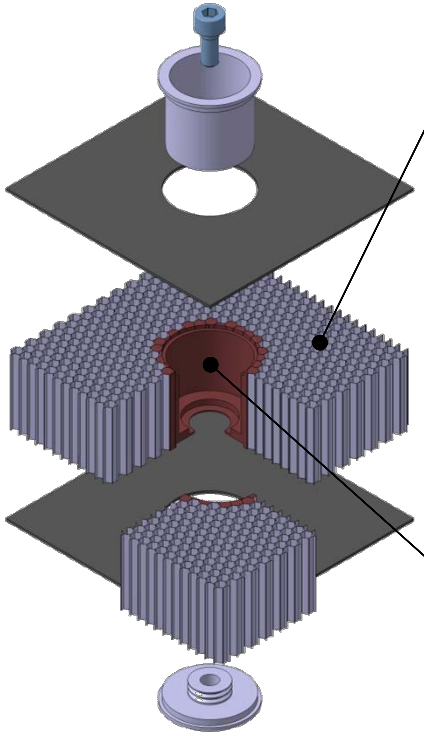
[1] Werte aus: Hartschäume:
Datenblatt_Hartschaum_AIREX_C70.40-200_Gaugler+Lutz_DB_2010
Datenblatt_Hartschaum_AIREX_T90_Gaugler+Lutz_DB_2011
Datenblatt_Hartschaum_Divinycell_H_35-250_DIAB_DB_2013
Datenblatt_Hartschaum_Divinycell_P_60-150_DIAB_DB_2012
Datenblatt_Hartschaum_Rohacell_31-110_IG+31-110_IG-F_Gaugler+Lutz_DB_2011
Datenblatt_Hartschaum_Rohacell_S_Evonik_DB_2011_V01

Honigwaben Aramid / Nomex:
Datenblatt_Honigwaben_Nomex_Hexcel_HexWeb_HRH-10_metrisch_DB_2015
Datenblatt_Honigwaben_Nomex_Plascore_PN2_Aerospace_Grade_metrisch_DB_2015
Datenblatt_Honigwaben_Nomex_Schütz_Coremaster_C1_metrisch_DB_2015
Datenblatt_Honigwaben_Nomex_Schütz_Coremaster_C2_metrisch_DB_2015
Datenblatt_Honigwaben_Nomex_Schütz_Coremaster_N636_metrisch_DB_2014
Datenblatt_Honigwaben_Nomex_Euro-Composites_ECA_metrisch_DB_1998

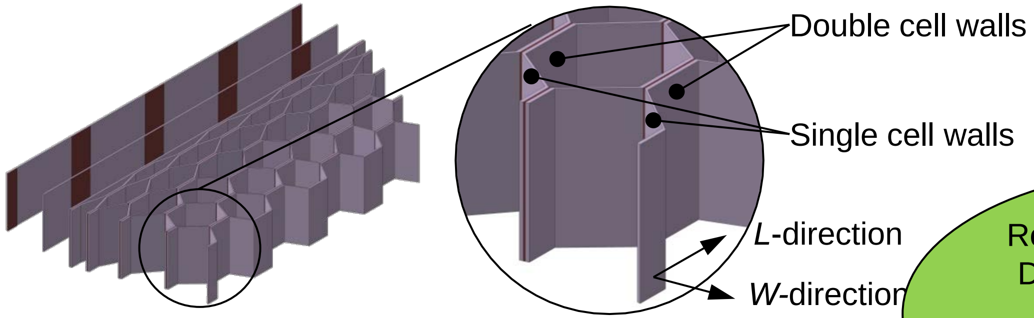
Honigwaben Aluminium 5052 + 5056:
Datenblatt_Honigwaben_Aluminium_Euro-Composites_ECA+ECA-R_metrisch_DB_2010
Datenblatt_Honigwaben_Aluminium_Euro-Composites_ECM_metrisch_DB_1993
Datenblatt_Honigwaben_Aluminium_Hexcel_HexWeb_CR_III_5052+5056_imperial_DB_2015
Datenblatt_Honigwaben_Aluminium_Plascore_PAMG-XR1_5056_imperial_DB_2015
Datenblatt_Honigwaben_Aluminium_Plascore_PAMG-XR1_5052_imperial_DB_2015

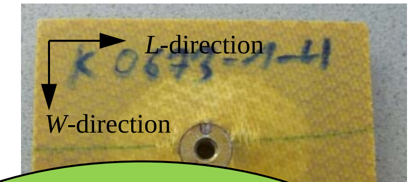
4. Insert sizing Approach

Influences on Load Carrying Capability: Anisotropic Honeycomb Material, Potting Shapes



1. Typical Honeycomb materials: Anisotropic shear strength properties due to assembly process.



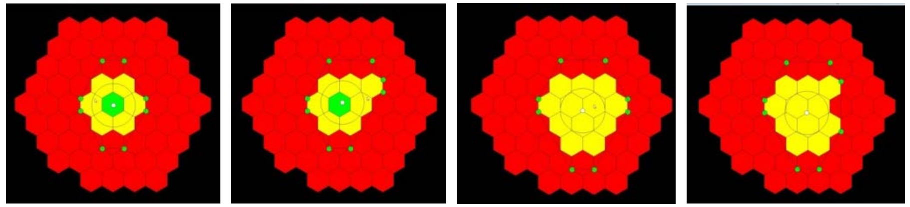


Rodriguez Ramirez, J. d. D. et al., ICA, ICCS 20, 05.09.2017: $\tau_{c,rz,crit,eff;Dio} = \mathbf{1,15} \cdot \tau_{c,W,typ}$

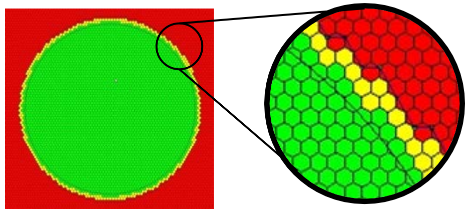
$$\boxed{\tau_{c,rz,crit}(\varphi) = \boldsymbol{\tau_{c,rz,crit,eff}} = \mathbf{1 \ldots 1,36} \cdot \boldsymbol{\tau_{c,W,typ}}}$$

2. Potting: Range of shapes and quantities in the honeycomb hexagonal grid.

$\boldsymbol{r_i/S_c = 1}$



$\boldsymbol{r_i/S_c = 30}$



r_i/S_c-ratio ↓↓: High influence of symmetry and Δn_{pcf} . r_i/S_c ↑↑ Negligible influence of symmetry and Δn_{pcf} !

$r_{ili} = r_{p,eff,min} \rightarrow r_i$

$$\boxed{r_{p,eff,min,He} = 0.9\, r_i + 0.7\, S_c}$$ [1]

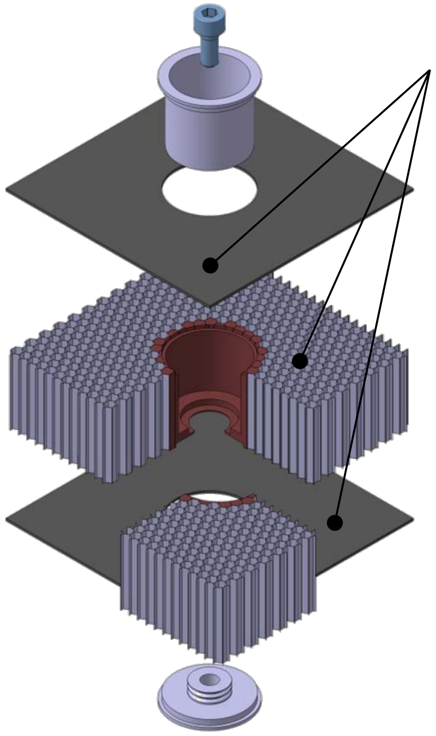
$$\boxed{r_{p,eff,min,max,Wol} = a_1 \cdot r_i + a_2 \cdot S_c}$$

→ **The anisotropic behavior of common honeycomb materials as well as the possible range of the potting must be respected!**

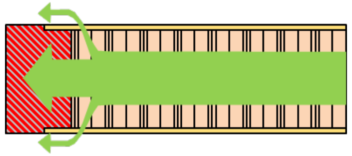
[1] Hertel, W., Paul, W. und Wagner, D. Standardisation Programme on Design Analysis and Testing of Inserts. [Hrsg.] ERNO Raumfahrttechnik GmbH Struct. Dept. [Report]. Bremen, Germany : ESTEC, 13. 02 1981. Bd. Final Report , S. 426.
[2] **Heimbs, Sebastian und Pein, Marc.** *Failure behaviour of honeycomb sandwich corner joints and inserts.* EADS Innovation Works. Composite Structures 89 : Elsevier, 2009. S. 575–588, Paper.

4. Insert sizing Approach

Influences on Load Carrying Capability: Sandwich: Geometry and Material Property Configurations



3. Varying core shear force proportions with different sandwich configurations.



vs.

→ High core-to-face sheet thickness ratio, low bending resistance of face sheets, high shear stiffness core of core material.

$$\boxed{\eta_{ld} = 1}$$ [1,2]

→ Low core-to-face sheet thickness ratio, high bending resistance of face sheets, low shear stiffness of core material.

$$\boxed{\eta_{ld} < 1}$$ [1,2]

$$r_{ili,min} = \frac{Q_{z,ll}}{\tau_{c,rz,crit} \cdot \left(t_{fs1} + \frac{h_c}{2}\right) \cdot 2\pi}$$

⇨

Final sizing formula respecting all crucial influences:

$$\boxed{\boldsymbol{r_{i,min} = \frac{F_{op,ll} \cdot \eta_{ld}}{a_{1,min} \cdot \tau_{c,rz,crit,eff} \cdot \left(h_c + t_{fs}\right) \cdot 2\pi} - S_c \frac{a_{2,min}}{a_{1,min}}}}$$

→ There is actually no core shear force reduction factor η_{ld} available for the specific insert load introduction ´type (ttt-, cold bonded insert load introduction)!

Validation? ⇩

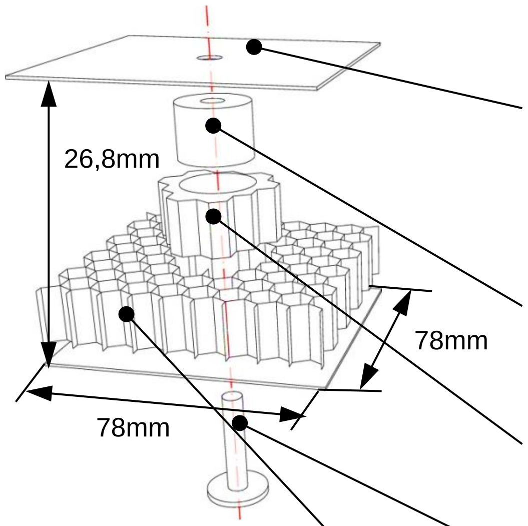
$$\boxed{\boldsymbol{F_{o,ll,th} = \frac{r_{p,eff,rl} \cdot \tau_{c,rz,crit,eff} \cdot \left(h_c + t_{fs}\right) \cdot 2\pi}{\eta_{ld}}}}$$

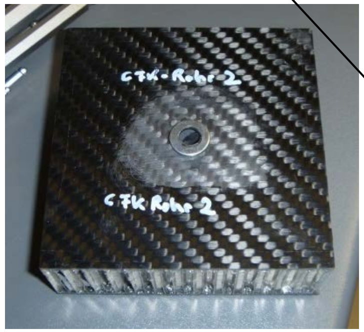
[1] Ericksen, Wilhelm S. The bending of circular Sandwich Plate under normal Load. [Hrsg.] Forest products Laboratory, Madison, Wisconsin 53705 Wood Engineering Research. [Paper]. Madison, Wisconsin, USA : US Department of agriculture, Forest Service, 1953. No. 1828, S. 35.
[2] Montrey, H. M. Bending of a circular Sandwich Plate by Load applied through an Insert. [Hrsg.] Madison, Wisconsin 53705 Forest products Laboratory. [Paper]. Madison, Wisconsin, USA : US Department of Agriculture, Forest Service, 1973. S. 31. In cooperation with the MIL-HDBK-23 Working Group on structural Sandwich Composites for Aerospace Vehicles .
[3] ECSS European Cooperation for Space Standardization. Space Engineering Insert Design Handbook. [Hrsg.] ESA-ESTEC. Noordwijk : s.n., 2011. Bde. ECSS-E-HB-32-22A. S. 331
[4] Hertel, W., Paul, W. und Wagner, D. Standardisation Programme on Design Analysis and Testing of Inserts. [Hrsg.] ERNO Raumfahrttechnik GmbH Struct. Dept. [Report]. Bremen, Germany : ESTEC, 13. 02 1981. Bd. Final Report , S. 426.

5. Comparison of Test to analytic Results

Test Definition: Specimen and Setup

Definition of test specimen for preliminary test





Face sheets: CFRP-PREPREG-panels with quasi-isotropic layup of 5 unidirectional and woven layers of endless carbon fiber T700 Torayca, epoxy matrix, $t_{fs,1,2}$= 0,85mm.

Insert element: Cylindrical ttt-insert, core connected, machined aluminium, $\varnothing$ = 26mm resp. r_i= 13mm.

Potting compound: Structural adhesive 3M ScotchWeld DP490**.**

Screw: M6 cylindrical head steel screw, grade 8.8, DIN ISO 4762**.**

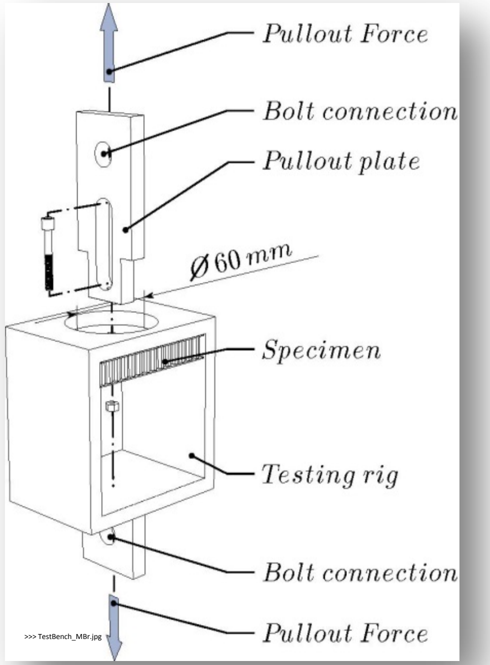
Honeycomb core: Aluminium honeycomb, Plascore PAMG-XR1-4.5-1/8-10-P-5056, S_c= 3,2mm, t_{hc} = 0,025 mm, ρ_c= 69kg/dm³, $\tau_{c,rz,crit,W}$ = 1,18MPa, h_c=25mm. [1,2]

Number of specimen: 2

Test setup for orthogonal insert pull-out

Testing machine

Test rig



- Testing machine: Zwick/Roell BZ1
- Force transducer: 20kNZ0 WN 812616
- Data program: Zwick/Roell, TestExpert II

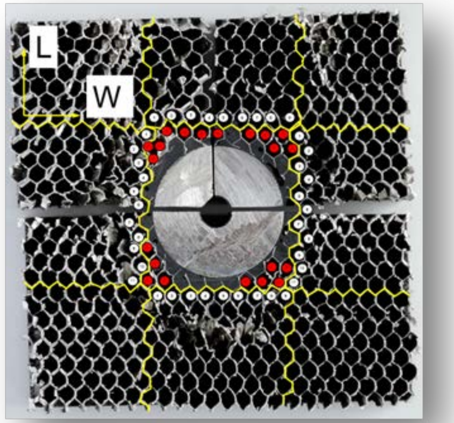
- Preload: 10N
- Testing speed: 6 mm/min
- Data rate: 10/sec

[1] Plascore Incorporated. PAMG-XR1 5056 Aluminium Honeycomb. v12.14 [Datenblatt]. Zeeland, Michigan, USA : s.n., 2014. www.plascore.com.
[2] Plascore GmbH & Co. KG. Report# 41137-123366-1. [Hrsg.] Feldborn 6, 55444 Waldlaubersheim Plascore GmbH & Co. KG. Inspection Certificate 3.1. according to EN 10204 for Aluminum Honeycomb. [Inspection Certificate]. Waldlaubersheim, Germany : s.n., 19. 08 2016. S. 1. Material: PAMG-XR1-4.5-1/8-10-P-5056, Coil Number: 42284373/1, Block Number: 113B0316, .

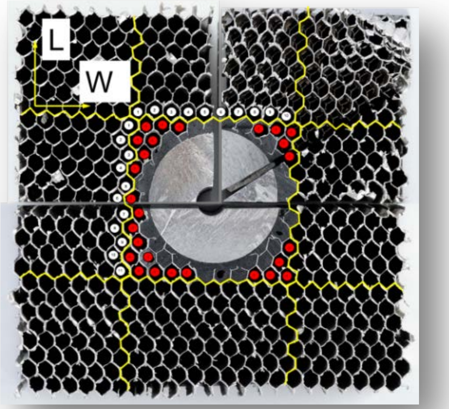
5. Comparison of Test to analytic Results

Analytic Prediction with sizing Approach: Calculation

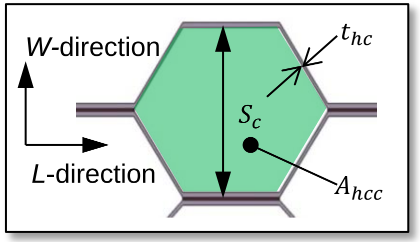
1. Real effective potting radius



Test specimen #1: $n_{pcf,1}$ = 78



Test specimen #2: $n_{pcf,2}$ = 83



$$r_{p,eff,rl} = \sqrt{\frac{n_{pfc} \cdot A_{hcc}}{\pi}} = \sqrt{\frac{n_{pfc} \cdot 3 S_c{}^2}{\pi \cdot \sqrt{3}}} \quad [1]$$

$$\boxed{\boldsymbol{r_{p,eff,rl,\#1} = 21,0mm}}$$

$$\boxed{\boldsymbol{r_{p,eff,rl,\#2} = 21,6mm}}$$

2. Calculation of homogenized honeycomb shear strength

$$\tau_{c,crit,eff,Heimbs} = \tau_{c,crit,W} \quad [2]$$

$$\boxed{\boldsymbol{\tau_{hc,rz,crit,eff,Hei} = 1,18MPa}}$$

$$\tau_{c,crit,eff,Hertel} = 1{,}36 \cdot \tau_{c,crit,W} \quad [1]$$

$$\boxed{\boldsymbol{\tau_{c,rz,crit,eff,Her} = 1,6\ MPa}}$$

3. Rearrangement of sizing formulation, calculation of theoretic critical first failure load

$$F_{o,ll,th} = \frac{r_{p,eff,rl} \cdot \tau_{c,rz,crit,eff,i} \cdot (h_c + t_{fs}) \cdot 2\pi}{\eta_{ld}}$$

$$\Downarrow$$

$$\boldsymbol{F_{o,ll,th,\#1}} = \frac{21{,}0mm \cdot 1{,}6\,N/mm^2 \cdot (25mm + 0{,}85mm) \cdot 2\pi}{1} = \boldsymbol{5457N}$$

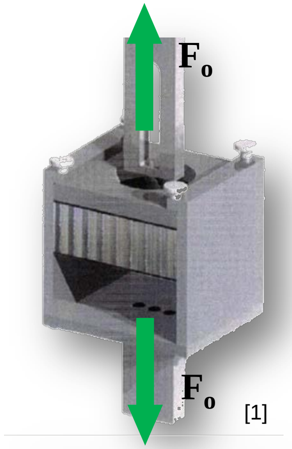
$$\boldsymbol{F_{o,ll,th,\#1}} = \frac{21{,}6mm \cdot 1{,}6\,N/mm^2 \cdot (25mm + 0{,}85mm) \cdot 2\pi}{1} = \boldsymbol{5638N}$$

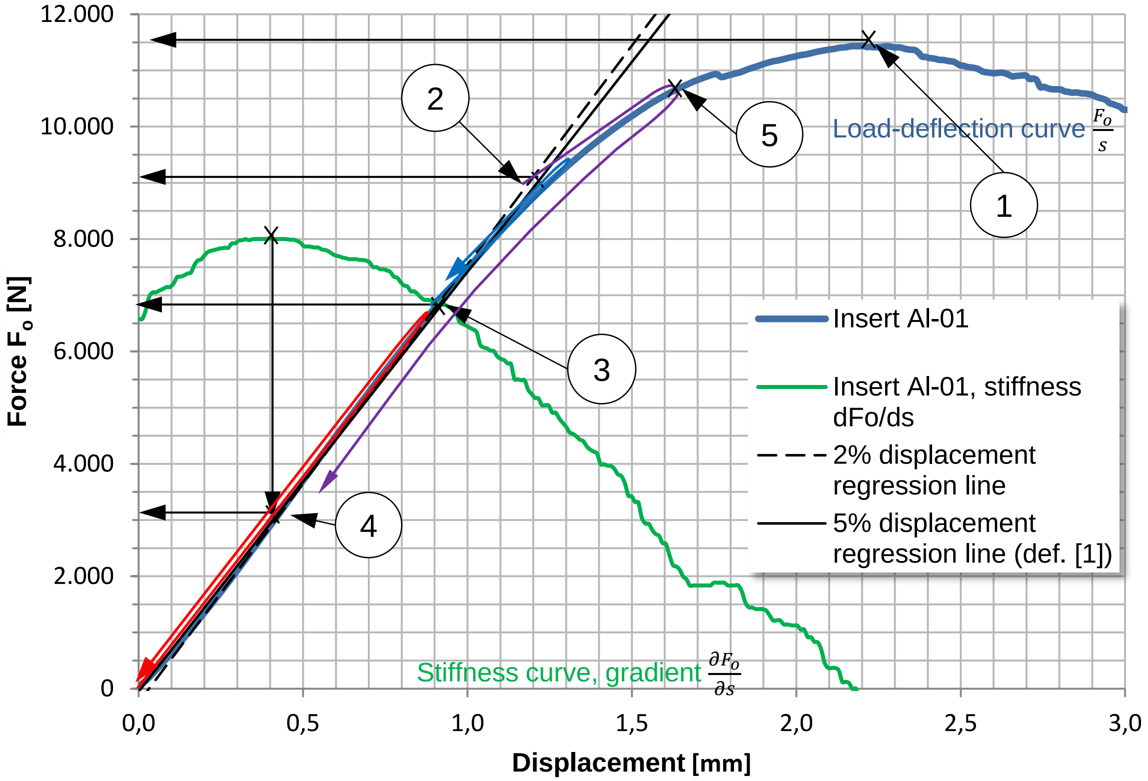
[1] Hertel, W., Paul, W. und Wagner, D. Standardisation Programme on Design Analysis and Testing of Inserts. [Hrsg.] ERNO Raumfahrttechnik GmbH Struct. Dept. [Report]. Bremen, Germany : ESTEC, 13. 02 1981. Bd. Final Report , S. 426.
[2] Heimbs, Sebastian und Pein, Marc. Failure behaviour of honeycomb sandwich corner joints and inserts. EADS Innovation Works. Composite Structures 89 : Elsevier, 2009. S. 575–588, Paper.

5. Comparison of Test to analytic Results

Divergent Test Data Interpretations

→ Which characteristic of the stiffness curve is to allocate to the first plastic core shear failure?





Five different methods of first failure load level allocation are common:

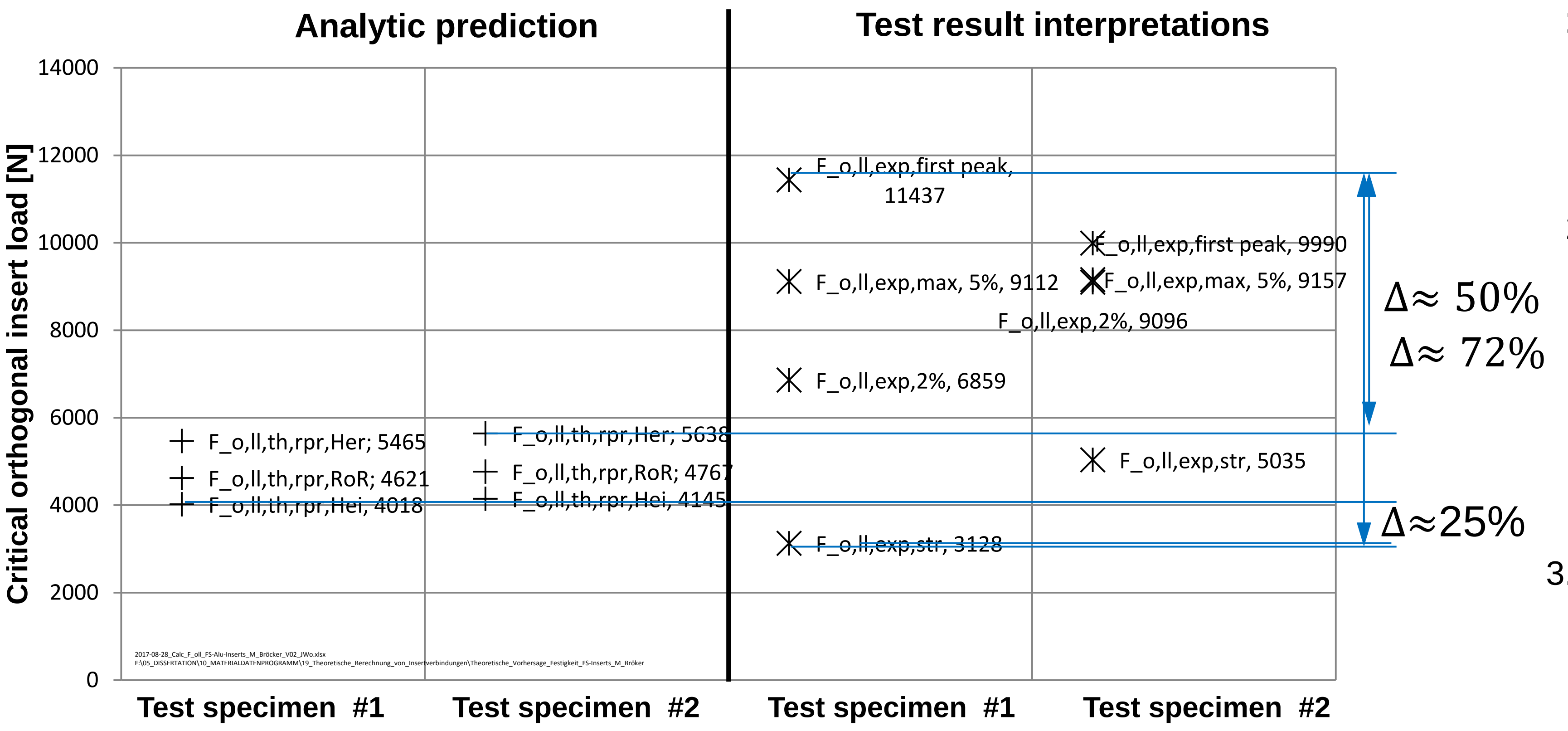
1. First peak. [1-8] $\boldsymbol{F_{o,ll,exp,fp,\#1} = 11437N}$
2. Intersection with 5% displacement regression line. [10] $\boldsymbol{F_{o,ll,exp,5\%,\#1} = 9112N}$
3. Intersection with 2% displacement regression line. [9] $\boldsymbol{F_{o,ll,exp,2\%,\#1} = 6859N}$
4. Point of maximal stiffness. $\boldsymbol{F_{o,ll,exp,str,\#1} = 3128N}$
5. Analysis of hysteresis tests. [11-12]

→ Several “state of the art” first irreversible failure interpretations deliver highly diverging results…

[1] Kim, Byoung Jung und Lee, Dai Gil. Characteristics of joining inserts for composite sandwich panels. [Hrsg.] Korea Advanced Institute of Science and Technology Department of Mechanical Engineering. Composite Structures. s.l., South Korea : Elsevier Science Ltd. , 2008. Bd. 86, S. 55–60.
[2] Song, Keun-Il, et al., et al. An experimental study of the insert joint strength of composite sandwich structures. [Hrsg.] Research Center for Aircraft Parts Technology, Gyeongsang National University School of Mechanical and Aerospace Engineering. Composite Structures. [Paper]. s.l., Republic of Korea : Elsevier Ltd., 03 2008. Bd. 86, 2008, S. 107–113.
[3] Lim, Jun Woo und Lee, Dai Gil. Development of the hybrid insert for composite sandwich satellite structures. [Hrsg.] Elsevier. Composites: Part A 42. 2011, A 42, S. 1040-1048.
[4] Heimbs, Sebastian und Pein, Marc. Failure behaviour of honeycomb sandwich corner joints and inserts. EADS Innovation Works. Composite Structures 89 : Elsevier, 2009. S. 575–588, Paper.
[5] Block, Joachim. Study on Carbon Fibre Tube Inserts, Summary report. [Hrsg.] Deutsches Zentrum für Luft- und Raumfahrt e.V. Institut für Strukturmechanik. [report]. Braunschweig, Germany : ESTEC /Contract No. 16822/02/ NL/PA, 2004. IB 131-2004/29.
[6] Bianchi, G., Aglietti, G. S. und Richardson, G. Optimization of bolted Joints connecting Honeycomp Panels. University of Southampton, School of Engineering Sciences : NN, 2006. Paper.Nguyen_K_H_Failure_behaviour_of_foam_based_sandwich_joints_under_pull-out_testing_CS_PA_2011
[7] Nguyen, Khanh-Hung, et al., et al. Failure behaviour of foam-based sandwich joints under pull-out testing. [Hrsg.] Research Centre for Aircraft Parts Technology, Gyeongsang National University, Jinju, Gyeongnam Department of Aerospace Engineering. Composite Structures. [Paper]. Gyeongnam, Fachaufsatz. South Korea : Elsevier Science Ltd. , 2012. Bd. 94, S. 617 - 624. doi:10.1016/j.compstruct.2011.08.027.
[8] Park_Y-B_Failure_characteristics_of_carbon-BMI-Nomex_sandwich_joints_in_various_hygrothermal_conditions_CPB_PA_2014J. Block. Study on carbon fibre tube inserts, synthesis of analysis and tests. Technical report, Deutsches Zentrum für Luft- und Raumfahrt e.V. Institut fur Strukturmechanik. Braunschweig, Germany, 2007.
[9] Roy, R., et al., et al. Testing and modeling of Nomex™ honeycomb sandwich panels with bolt insert. [Hrsg.] Research Center for Aircraft Parts Technology, Gyeongsang National University Department of Aerospace Engineering. Composites: Part B. [Paper]. s.l., South Korea : Elsevier Science Ltd. , 2014. Bd. 56, S. 762 – 769.
[10] Block, Joachim. Technical Note 4, Test Report. [Hrsg.] Inst. FA Deutsches Zentrum für Lift- und Raumfahrt DLR. Carbon Fibre Tube Inserts (Part 2). [Interner Bericht]. Braunschweig, Germany : s.n., 2007. S. 1 - 49. IB 131-2007 I 06.
[11] Bunyawanichakul, P., Castanie, B. und Barrau, J.-J. Experimental and numerical analysis of inserts in sandwich structures. [Hrsg.] LMS Sup'Aéro, Toulouse IGMT. Applied Composite Materials. [Paper]. Toulouse, France : Springer, 2005. Bd. 12, S. 177 - 191. DOI: 10.1007/s10443-005-1122-6.
[12] Bunyawanichakul, P., Castanié, B. und Barrau, J.-J. Non-linear finite element analysis of inserts in composite sandwich structures. Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University Bangkok. Composites: Part B 39 : Elsevier, 2008. S. 1077–1092, Paper /

5. Comparison of Test to analytic Results

Deviations between theoretical and practical Results



Theoretical values considering the individual real potting radii $r_{p,b,1,2}$ and $\Delta\tau_{hc,crit,eff}$ from different core shear approaches.

Test results considering different methods of critical load level interpretations.

1. **Way too high divergences** between different **test result interpretations**: Which one represents the first irreversible failure?
2. The minimal test result ("maximal stiffness point" failure interpretation) of specimen #1 is smaller than the minimal analytic prediction. → **Danger of critical overestimation by the analytic prediction!**
3. Analytic results compared to "first peak" and "5% regression line" failure test interpretations. → Much to conservative results due to underestiamtion, **danger of an oversizing of the insert load introduction!**

→ In their actual forms, neither the analytical approach nor the test evaluation are sufficient for an effective sizing of insert elements!

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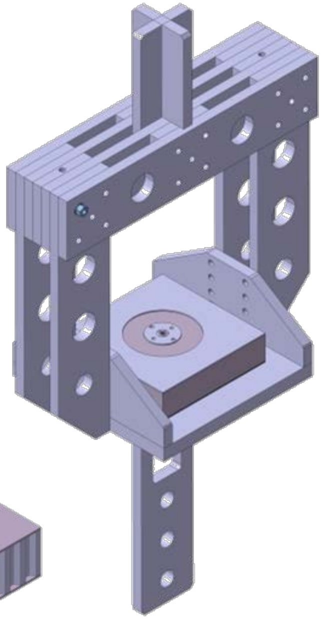
6. Way forward

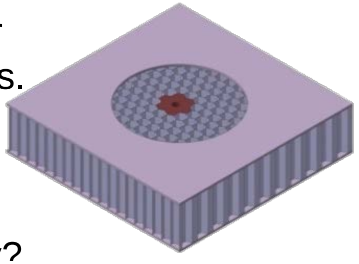
Issue #1: Different first failure load level interpretations of test results.

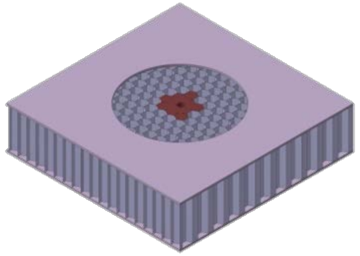
1. Improved test procedure by hysteresis tests and cutting samples → Deduction of improved test data interpretation process.



Issue #2: Divergent core shear homogenization approaches.

2. Tests with special specimen with locally removed face sheets: Observation of shear damage process of individual core cell walls.
    - Support of improved test data interpretation process.
    - Is it possible to measure the effective core shear strength ($\tau_{c,crit,eff}$) directly?





Issue #3: No shear force reduction factor η_{ld} for the certain insert configuration!

3. Deduction of correct core shear force reduction factor η_{ld} for the certain insert type with the help of the higher order sandwich plate theory (HSAPT).

$$\eta_{ld} = f\left(h_c, t_{fs}, G_{c,W,typ}, E_{fs,eff}, \nu_{fs}, r_{spprt,\ldots}\right)$$

→ Three main measures to counteract the large discrepancies of theoretical to test results!

Thanks for your Attention!

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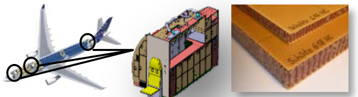
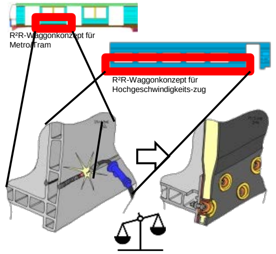
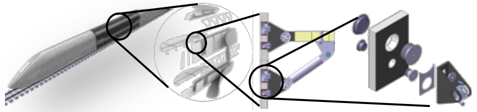


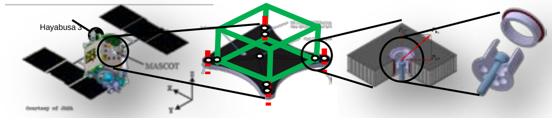
Innovative Galley (InGa)



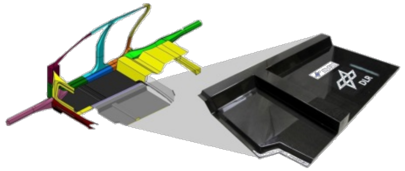
Roll to Rail-Project (R²R)



Next Generation Train Project (NGT II – III)



MASCOT II



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